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The cost of integration of parabolic trough CSP plants in isolated Mediterranean power systems

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ABSTRACT

In this work, a technical and economic analysis concerning the integration of parabolic trough concentrated solar power (CSP) technologies, with or without thermal storage capability, in an existing typical small isolated Mediterranean power generation system, in the absence of a feed-in tariff scheme, is carried out. In addition to the business as usual (BAU) scenario, five more scenarios are examined in the analysis in order to assess the electricity unit cost with the penetration of parabolic trough CSP plants of 50 MWe or 100 MWe, with or without thermal storage capability. Based on the input data and assumptions made, the simulations indicated that the scenario with the utilization of a single parabolic trough CSP plant (either 50 MWe or 100 MWe and with or without thermal storage capability) in combination with BAU will effect an insignificant change in the electricity unit cost of the generation system compared to the BAU scenario. In addition, a sensitivity analysis on natural gas price, showed that increasing fuel prices and the existence of thermal storage capability in the CSP plant make this scenario marginally more economically attractive compared to the BAU scenario.

Contents

1. Introduction

Solar energy is a renewable source that is inexhaustible and is locally available. It is a clean energy source that allows for local energy independence. The sun's power that is reaching the earth annually is typically about 1000 W/m^2, although availability varies with location and time of year. Capturing solar energy typically requires equipment with a relatively high initial capital cost. However, in some cases, over the lifetime of the solar equipment, these systems can prove to be cost competitive, as compared to conventional energy technologies [4].

Concentrated solar power (CSP) technologies utilize the sun as a source of heat which can be exploited by concentrating that heat and using it to drive a heat engine to produce power. As such, CSP power generation is much more closely related to traditional forms of power generation based on fossil fuel combustion which also rely on heat engines to convert heat into electrical energy. Moreover, the concentrated solar power potential in the Mediterranean region is immense. This is due to the high level of solar irradiation available throughout most of the year in the region and also the geographical morphology in some Mediterranean countries (in particular the Mediterranean islands and the North

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Africa countries bordering the Sahara desert). The advantages of Mediterranean countries in terms of CSP electricity generation have been reported in the conclusions of numerous relevant European research projects [10], and also highlighted during the inauguration of the Mediterranean Union during the EU Paris summit in 2008 [1]. CSP generation in the Mediterranean countries forms the building block of the Mediterranean Solar Plan, a strategic energy plan, which aims to further develop and materialize the physical connection of the existing European electricity network with the future electricity networks of North African and other Mediterranean countries to be based on solar thermal power generation technologies.

Current solar thermal power technologies are distinguished in the way they concentrate solar radiation, such as (a) parabolic trough systems, (b) solar tower systems and (c) solar dish systems. The direct radiation is concentrated using reflectors and the energy concentrated in this way is transformed into steam, which is used to drive conventional electricity generators. An overview of the most common available solar thermal power technology and of thermal storage is provided in [3,4].

Having regarded that the electricity sector in the Mediterranean region is currently a major contributor to each Mediterranean country's total CO_2 emissions, it is important to begin considering the possibility of integrating CSP. As a first step in this direction, we can analyze the new technical and economic status that the integration of such technology will affect the long term strategic planning of each Mediterranean country. Already, in a recent study [3], a feasibility analysis was carried out in order to investigate whether the installation of a parabolic trough CSP technology for power generation in a Mediterranean isolated power system is economically feasible. One of the conclusions of the study was that the size of the solar thermal plant is critical for the viability of the investment.

In this work, a technical and economic analysis concerning the integration of CSP parabolic trough technologies (with or without thermal storage capability) in an existing isolated Mediterranean power generation system, in the absence of a feed-in tariff scheme, is carried out. For the simulations, the WASP IV [8] software package is employed, which is a specialized simulation software used widely for the selection of the optimum expansion planning of the generation system. The electricity unit cost of the generation system for various investigated scenarios can then be calculated.

In Section 2, a brief description of the test case Mediterranean isolated power generation system is provided. In Section 3, the simulation procedure is presented and in Section 4, the results are discussed. Finally the conclusions are summarized in Section 5.

2. Description of test case system—the Cyprus power system

A typical example of a small, geographically isolated power system considered in this study is the Cyprus power system. As is the case with most islands in the Mediterranean sea Cyprus is an island with no indigenous hydrocarbon energy sources. This means that its power generation system operates in isolation and totally relies on imported fuels for electricity generation. Currently, the primary imported fuel used in electricity generation is heavy fuel oil (HFO) with a contribution of 92% of the energy mix and the remaining 8% being diesel.

Cyprus power generation system consists of three thermal power stations with a total installed capacity of 1388 MWe. Moni power station consists of 6×30 MWe steam turbines and 4×37.5 MWe gas turbines. Dhekelia power station consists of 6×60 MWe steam turbines and a 50 MWe internal combustion engines block. Finally, Vasilikos power station consists of 3×130 MWe steam turbines, a 220 MWe combined cycle technology and a 38 MWe gas turbine. The steam units at Vasilikos are used for base load generation, while the steam units of Dhekelia are used for base and intermediate load generation. The steam units at Moni as well as the gas turbines are mainly used during system peak loading. All stations use HFO for the steam turbine units and gasoil for the gas turbine units. The combined cycle unit will use gasoil as fuel for its first few years of its operation until the arrival of natural gas in Cyprus, which is expected to be available on the island after 2014.

Future short and medium term expansion plans for the Cyprus generation system involve the commissioning of two additional natural gas combined cycle units which are expected to be installed at Vasilikos power station with a capacity of 220 MWe each by the year 2014. Also in 2010 an additional internal combustion engines block with a capacity of 50 MWe at Dhekelia power station is expected to be online.

Concerning the penetration of renewable energy sources for power generation, it is currently negligible in Cyprus. It amounts to a few cases of small PV systems installed in homes, and to a smaller degree, biomass gasification (using wood, agricultural wastes, olive kernels, almond husks, etc.). Despite the almost zero penetration of renewable energy sources technologies in Cyprus, a large amount of licenses have been recently granted pertaining to electricity generation from wind parks and to a smaller extend, biomass plants. The wind park installations that have been so far approved account for a total generation of 467 MWe, while there are still pending applications for approval for another 246 MWe of wind energy. The biomass plants that have so far been approved amount to approximately 8 MWe. Regarding CSP technologies, various license applications are currently pending approval with a total capacity of 220 MWe [9].

By considering the annual generated electrical energy on the island of Cyprus since 1979 and the corresponding period peak load demand, the average annual increase of the total generated electrical energy and of the peak load demand up to and including the year 2008 is around 6% for both cases. This growth rate forms the basis for the official Cyprus load forecast for the period 2009–2029 as approved and published by the Cyprus Energy Regulatory Authority [9].

3. Simulation of the power generation system

In this section, a technical and economic analysis is carried out in order to examine the effect of the expected penetration of parabolic trough CSP plants (with or without thermal storage capability) on the electricity unit cost of the future Cyprus generation system. The operation of the generation system is simulated using the Wien Automatic System Planning IV (WASP IV) package [8]. For the purposes of this work, the parabolic trough CSP technology is chosen mainly due to its technological maturity. Firstly, the software used for the simulations is briefly introduced and then, the input data and the assumptions are discussed.

3.1. Optimization software

The future generation system of Cyprus power industry is simulated using the Wien Automatic System Planning IV (WASP IV) package which is widely used for automatic generation planning [8]. The WASP IV software package finds the optimal expansion plan for a given power generating system over a period of up to 30 years [5]. The foreseen seasonal load duration curves, the efficiency, the maintenance period and the forced outage rate of each generating plant are taken into account. The objective function, which shows the overall cost of the generation system (existing and candidate generating plants), is composed of several components. The components, related to the candidate generating

units, are the capital cost and the salvage capital cost. The components, which are related to both the existing and candidate generating units are the fuel cost, the fixed operation and maintenance costs, such as, staff cost, insurance charges, rates and fixed maintenance, the variable operation and maintenance costs, such as, spare parts, chemicals, oils, consumables, town water and sewage. The cost to the national economy of the energy not served (ENS) because of shortage of capacity or interruptions is, also, taken into consideration.

The WASP package was originally developed in the United States for the needs of the International Atomic Energy Agency (IAEA) [8]. It is the most frequently used and best-proven program for electric capacity expansion analysis. It is used for long-term expansion planning and compares the total costs for the whole generation system for a number of candidate units. In the production simulation of WASP, a one-year period is divided into, at most, 12 sub-periods for each of which probabilistic simulation is applied. Equivalent load duration curves in the probabilistic simulation are approximated using Fourier series. The Fourier expansion makes it computationally simple to convolve and deconvolve generating units in the probabilistic simulation. The decision of the optimum expansion plan is made by the use of forward dynamic programming. The number of units for each candidate plant type that may be selected each year, in addition to other practical factors that may constrain the solution is specified. If the solution is limited by any such constraints, the input parameters can be adjusted and the model re-run. The dynamic programming optimization is repeated until the optimum solution is found. Each possible sequence of power units added to the system (expansion plan) meeting the constraints is evaluated by means of a cost function (the objective function), which is composed of (a) capital investment costs, I, (b) salvage value of investment costs, S, (c) fuel costs, F, (d) non-fuel operation and maintenance costs, M, and (e) cost of energy not served, Φ.

Thus,

$$B_j = \sum_{t=1}^{T} I_{jt} - S_{jt} + F_{jt} + M_{jt} + \Phi_{jt}, \tag{1}$$

where B_j is the objective function attached to the expansion plan j, t is the time in years (1, 2, ..., T) and T is the length of the study period (total number of years). All costs are discounted to a reference date at a given discount rate. The optimum expansion plan is the min B_j among all j.

3.2. Data and assumptions

A parabolic trough CSP plant in Cyprus can approximately operate with no thermal storage for five hours per day (5 h/day) whereas for daily operating hours greater than 5 h, thermal storage is necessary with direct effect on plant capital cost (greater solar field and land area required) and electricity production (power production is increased due to the increased operating hours). The study horizon covers a period of 30 years from 2010 up to 2039 in which six different technology scenarios are examined as candidates for the expansion of the Cyprus power generation system. For the simulations we employ WASP IV software package with all costs updated to 2010 values. In particular, the horizon of this study covers the period 2010–2039 with an assumed discount rate of 6%.

In addition to the business as usual (BAU) scenario for the future power generation expansion of the Cyprus generation system, which considers the natural gas combined cycle plants as the only candidate option, five more scenarios are examined in the analysis in order to assess the electricity unit cost of the future Cyprus generation system with the expected penetration of parabolic trough CSP plants. In four of these scenarios the natural gas combined cycle plants remain a candidate option for the system expansion, however, the Cyprus generation system is additionally integrated with one CSP plant (with or without thermal storage capability) assumed to have become commissioned in 2014.

The remaining scenario considers a 50 MWe parabolic trough CSP plant with 24 h/day operation (19 h/day thermal storage capability) as the only candidate option for the future expansion of the existing Cyprus system. Such CSP technology is not currently available commercially. The major obstacle to be overcome is the size, the operational issues and the cost of the necessary storage tanks required for 19 h of thermal storage. Extensive research and development is currently underway using various storage mediums that can enable this technology to materialize in an economically viable way [2,6].

For the purposes of this work, a parabolic trough CSP plant in Cyprus can approximately operate with no thermal storage for 5 h/day. For daily operating hours greater than 5 h, thermal storage is necessary with direct effect on plant capital cost (greater solar field and land area required) and electricity production (power production is increased due to the increased operating hours). In this work, 1 operating hour refers to the corresponding hourly maximum electricity production from the parabolic trough CSP plant, i.e., for 50 MWe capacity plant, the electricity generation for 1 h will be 50 MWh.

Therefore, all the scenarios examined in this work are listed below:

(a) Expansion with natural gas combined cycle technologies of 220 MWe capacity, which is considered as the BAU scenario.
(b) Expansion with one 50 MWe parabolic trough CSP plant, operating hours of 5 h/day (no thermal storage), in combination with BAU.
(c) Expansion with one 100 MWe parabolic trough CSP plant, operating hours of 5 h/day (no thermal storage), in combination with BAU.
(d) Expansion with one 50 MWe parabolic trough CSP plant, operating hours of 15 h/day (10 h thermal storage), in combination with BAU.
(e) Expansion with one 100 MWe parabolic trough CSP plant, operating hours of 15 h/day (10 h thermal storage), in combination with BAU.
(f) Expansion with parabolic trough CSP technologies of 50 MWe capacity, operating hours 24 h/day (19 h thermal storage).

The technical and economic parameters for each of the candidate power generation units are shown in Tables 1 and 2, respectively. The study does not take into consideration any land acquisition costs for the candidate power generation units [3]. The fuel costs for HFO (1% sulphur), gasoil and LNG (including the cost of regasification) for the period under investigation, were based on a long term forecast scenario with an average HFO price of 12.1US$/GJ, an average diesel price of 20.5US$/GJ and an average LNG price of 7.9US$/GJ. However, in order to examine the effect of natural gas price on the optimum generation expansion planning, a sensitivity analysis has been, also, carried out with various LNG prices (the HFO and gasoil prices remain unchanged), that is 4.9US$/GJ, 6.4US$/GJ and 9.4US$/GJ.

The technical and economic parameters of the parabolic trough CSP plant were estimated using the Solar Advisor Model (SAM) software tool, version 2009.10.2 [7] provided by the National Renewable Energy Laboratory (NREL), USA. For the purposes of the analysis, the CSP plant is a concentrated parabolic trough solar plant with a solar field area of 510,000 m^2 with 4 solar collector assemblies (SCA) per row. Distance between each row was taken to be 17.5 m while the distance between each SCA was 1 m. The solar

Table 1
Candidate technologies technical parameters.

Option no.	Technology	Fuel type	Maximum net load MWe	Minimum operating load MWe	Heat rate at maximum load kJ/kWh	Heat rate at minimum load kJ/kWh	Average incremental heat rate kJ/kWh	Forced outage %	Yearly scheduled maintenance days
1	Combined cycle (BAU)	Natural gas	220	70	6866	6965	6820	4.0	30
2	Parabolic trough CSP plant with 5 h/day operation	Solar irradiation	50	25	–	–	–	79.0	40
3	Parabolic trough CSP plant with 5 h/day operation	Solar irradiation	100	46	–	–	–	79.0	40
4	Parabolic trough CSP plant with 15 h/day operation	Solar irradiation	50	25	–	–	–	39.0	40
5	Parabolic trough CSP plant with 15 h/day operation	Solar irradiation	100	46	–	–	–	39.0	40
6	Parabolic trough CSP plant with 24 h/day operation	Solar irradiation	50	25	–	–	–	2.0	40

Table 2
Candidate technologies economic parameters.

Option no.	Technology	Fuel type	Capacity	Capital cost	Fuel net calorific value	Fuel cost		Fixed O&M	Variable O&M
			MWe	US$/kWe	GJ/t	US$/t	US$/GJ	US$/kW-month	US$/MWh
1	Combined cycle (BAU)	Natural gas	220	1063	49.7	362.8	7.3	1.50	1.50
2	Parabolic trough CSP plant with 5 h/day operation	Solar irradiation	50	5000	0	0	0	4.16	0.70
3	Parabolic trough CSP plant with 5 h/day operation	Solar irradiation	100	5000	0	0	0	4.16	0.70
4	Parabolic trough CSP plant with 15 h/day operation	Solar irradiation	50	6400	0	0	0	4.16	0.70
5	Parabolic trough CSP plant with 15 h/day operation	Solar irradiation	100	6400	0	0	0	4.16	0.70
6	Parabolic trough CSP plant with 24 h/day operation	Solar irradiation	50	7680	0	0	0	4.16	0.70

collector used is the EuroTrough collector with each solar collector having a length of 150 m and an aperture area of 817.5 m^2. The average focal length of each collector is 2.1 m. The heat transfer fluid used is the Hitec XL fluid with a working temperature range of 293–391 °C. The power block includes a condensing steam turbine with reheat cycle in a wet cooling steam cycle. The thermal energy storage technology employed is the two-tank solar salt technology, capable of achieving up to 10 equivalent full load hours of operation to the power block. Finally, no feed-in tariff scheme is considered in the economics of the parabolic trough CSP plant.

4. Results and discussion

In this section the base case (LNG average price of 7.9US$/GJ) results and the sensitivity analysis results (LNG prices 4.9US$/GJ, 6.4US$/GJ and 9.4US$/GJ) are discussed.

4.1. Base case results

The Cyprus generation system electricity unit cost for each of the six scenarios investigated is shown in Fig. 1. Based on the results shown, it is clear that the least cost option for the future expansion of the Cyprus generation system is the expansion with CSP technologies of 50 MWe capacity with operating hours of 24 h/day (19 h thermal storage). However, as already mentioned, this technology is currently not a proven commercial technology but it is under continuous research and technological development. It remains to be seen in the near future, whether such technology can become operational and at what cost [2,6].

The remaining five scenarios for generation system expansion exhibit only a marginal difference in terms of generation system electricity unit cost. The minor difference between the electricity unit costs of these scenarios mean that the expansion of the generation system with a single 50 MWe or 100 MWe parabolic trough CSP plant in combination with natural gas combined cycle technologies will not effect a significant electricity unit cost change in the generation system compared to the expansion based on the BAU scenario.

Moreover, it is shown in Fig. 1 that lower generation system electricity unit costs are achieved when a 50 MWe parabolic trough CSP plant is employed in the system expansion rather than a 100 MWe parabolic trough CSP plant, and also when the parabolic trough CSP plants with thermal storage capability are employed. The latter is clear because the system electricity unit cost in the last two scenarios employing thermal storage capability (i.e. one 50 MWe parabolic trough CSP with operating hours of

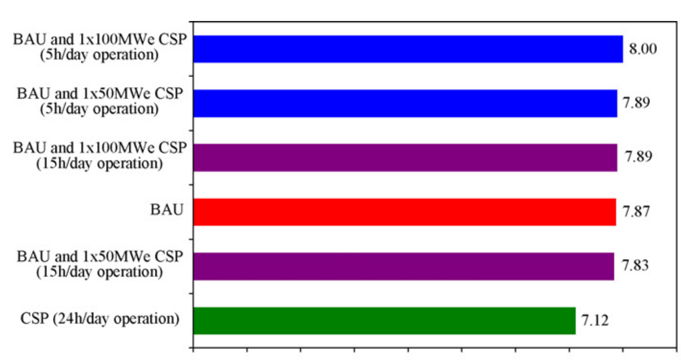

Fig. 1. Generation system electricity unit cost in real prices (base case).

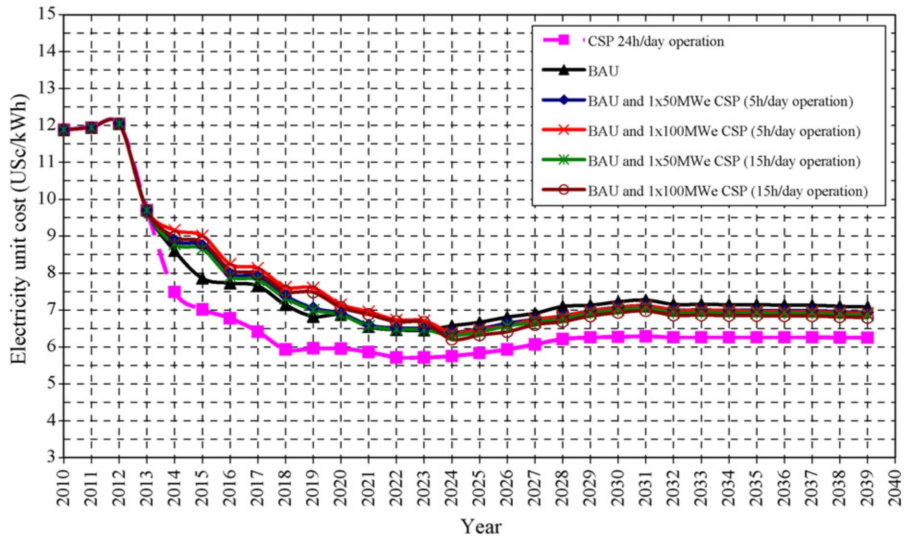

Fig. 2. Generation system annual electricity unit cost in real prices (base case).

15 h/day in combination with BAU and one 100 MWe parabolic trough CSP with operating hours of 15 h/day in combination with BAU) is lower compared to the scenarios without any thermal storage capability.

The annual generation system electricity unit cost (in real prices) for each of the scenarios investigated is illustrated in Fig. 2. It can be observed that between the years 2010–2014, the generation system electricity unit cost decreases substantially year by year due the introduction of more efficient technologies (already planned combined cycle technologies). Up to year 2024, and excluding the scenario of system expansion with parabolic trough CSP technologies of 50 MWe capacity with operating hours 24 h/day (19 h thermal storage), the BAU scenario is consistently the most economic option.

In the case of the BAU scenario, eight 220 MWe natural gas combined cycle plants are being introduced during the period of 2014–2029. The annual installed capacity, in the case of the BAU scenario is presented in Fig. 3. The expected annual level of the Cyprus system reserve margin (defined as the amount by which the generation system total electric power capacity exceeds maximum electric demand) is shown in the case of the BAU scenario up to the year 2039 in Fig. 4. From a system reliability point of view it is clear that the implementation of the 220 MWe natural gas combined cycle plants will not disrupt the reliability and stability of the power system since the level of reserve margin is constantly maintained above the threshold of 20%. Finally, the installed capacity mixture of the generation system in the case of the BAU scenario is shown in Fig. 5. It is evident that the currently used HFO fired steam turbines are being slowly phased out from the generation system, being substituted by natural gas combined cycle technology plants which start to become operational after year 2014.

4.2. Sensitivity analysis results

The price of LNG depends on long term contracts based mainly on the required annual volumes, therefore, safe predictions of price cannot be made. In order to examine the effect of natural gas price to the optimum generation expansion planning, the analysis was also carried out using different values of LNG prices, such as, 4.9US$/GJ, 6.4US$/GJ and 9.4US$/GJ. The results obtained regarding the generation system electricity unit cost from this sensitivity

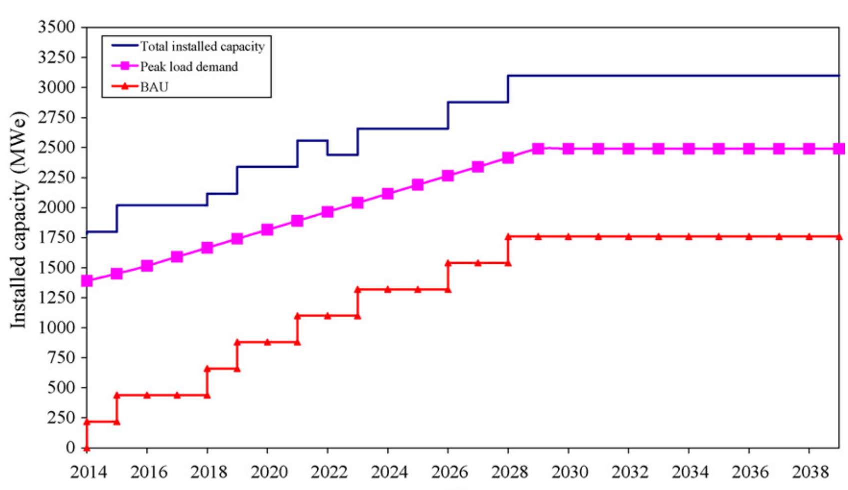

Fig. 3. Base case installed capacity and phasing for the BAU expansion scenario.

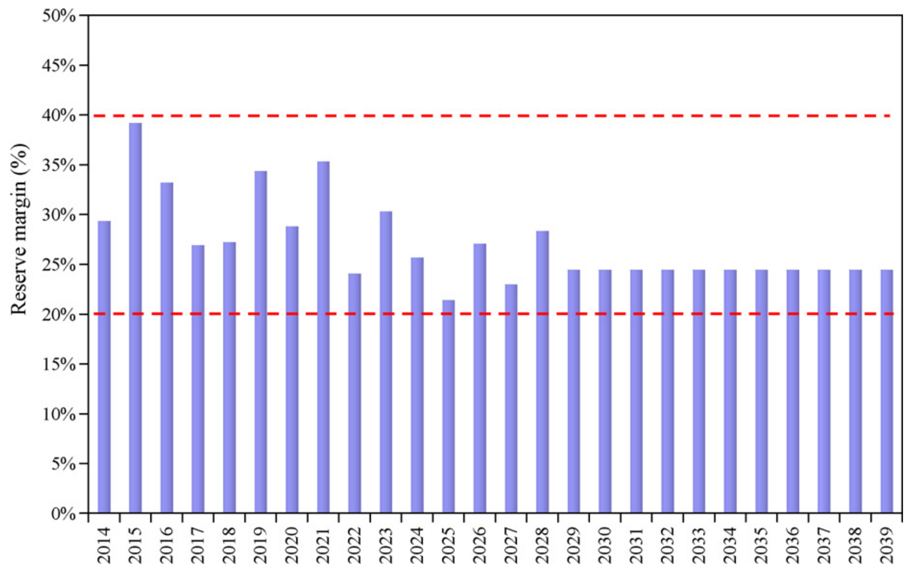

Fig. 4. Base case level of annual reserve margin for base case BAU expansion scenario.

Table 3
Sensitivity analysis results in real prices (including base case scenario).

Option no.	Candidate technology	Generation system Electricity unit cost (US$c/kWh)
LNG price 4.9US$/GJ		
f	CSP (24 h/day operation)	6.79
c	BAU and 1 × 100 MWe CSP (5 h/day operation)	6.42
e	BAU and 1 × 100 MWe CSP (15 h/day operation)	6.35
b	BAU and 1 × 50 MWe CSP (5 h/day operation)	6.30
d	BAU and 1 × 50 MWe CSP (15 h/day operation)	6.26
a	BAU	6.26
LNG price 6.4US$/GJ		
c	BAU and 1 × 100 MWe CSP (5 h/day operation)	7.22
e	BAU and 1 × 100 MWe CSP (15 h/day operation)	7.13
b	BAU and 1 × 50 MWe CSP (5 h/day operation)	7.10
a	BAU	7.07
d	BAU and 1 × 50 MWe CSP (15 h/day operation)	7.06
f	CSP (24 h/day operation)	6.98
Base case scenario (LNG price 7.9US$/GJ)		
c	BAU and 1 × 100 MWe CSP (5 h/day operation)	8.00
e	BAU and 1 × 100 MWe CSP (15 h/day operation)	7.89
b	BAU and 1 × 50 MWe CSP (5 h/day operation)	7.89
a	BAU	7.87
d	BAU and 1 × 50 MWe CSP (15 h/day operation)	7.83
f	CSP (24 h/day operation)	7.12
LNG price 9.4US$/GJ		
c	BAU and 1 × 100 MWe CSP (5 h/day operation)	8.82
b	BAU and 1 × 50 MWe CSP (5 h/day operation)	8.72
a	BAU	8.71
e	BAU and 1 × 100 MWe CSP (15 h/day operation)	8.68
d	BAU and 1 × 50 MWe CSP (15 h/day operation)	8.65
f	CSP (24 h/day operation)	7.34

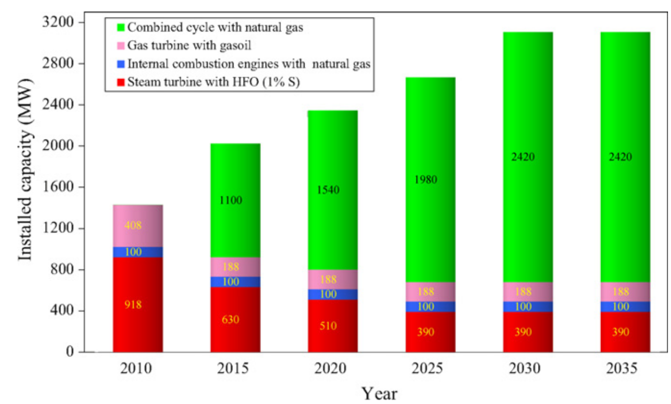

Fig. 5. Base case generation system installed capacity mixture for the BAU expansion scenario.

analysis for each LNG price are summarized in Table 3 and in Fig. 6 while the generation system annual electricity unit cost (in real prices) for the different LNG prices examined (4.9US$/GJ, 6.4US$/GJ and 9.4US$/GJ) are illustrated in Figs. 7–9.

The results for all the LNG prices examined in the sensitivity analysis confirm the conclusion of the base case, that there are only marginal differences in system electricity unit cost across each of the scenarios investigated - with the exception of the parabolic trough CSP technologies of 50 MWe capacity with operating hours 24 h/day (19 h thermal storage). Therefore, irrespective of the actual LNG price, the expansion of the generation system with a single 50 MWe or 100 MWe parabolic trough CSP plant in combination with BAU will not effect a significant electricity unit cost change in the generation system compared to the expansion based on the BAU scenario.

It can also be observed from these results that in the case of LNG price of 4.9US$/GJ, the marginally least cost technology for the expansion of the generation system is the natural gas combined cycle of 220 MWe capacity (BAU scenario). However, as the price of LNG increases, the options of generation system expansion with a single 50 MWe or 100 MWe parabolic trough CSP plant with thermal storage capability in combination with BAU gradually become marginally more economically attractive than the BAU expansion scenario.

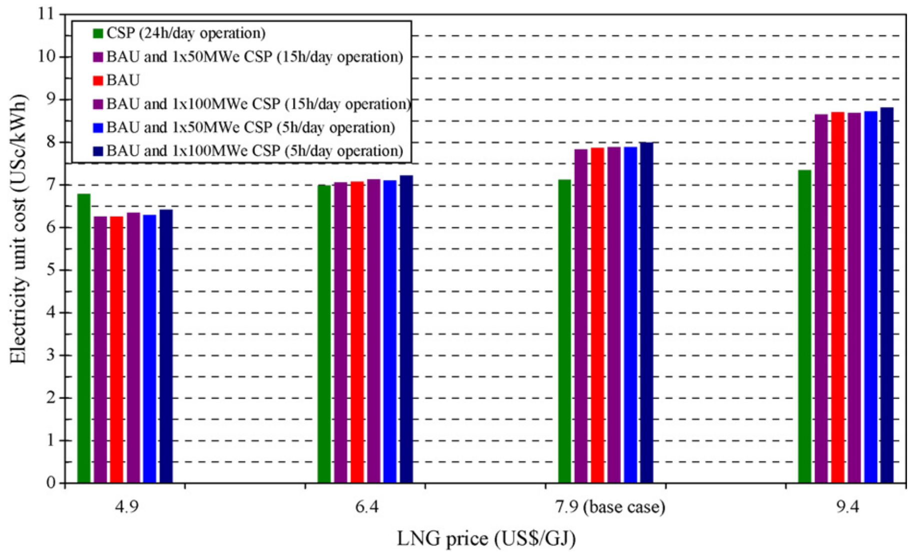

Fig. 6. Generation system electricity unit cost in real prices (sensitivity analysis).

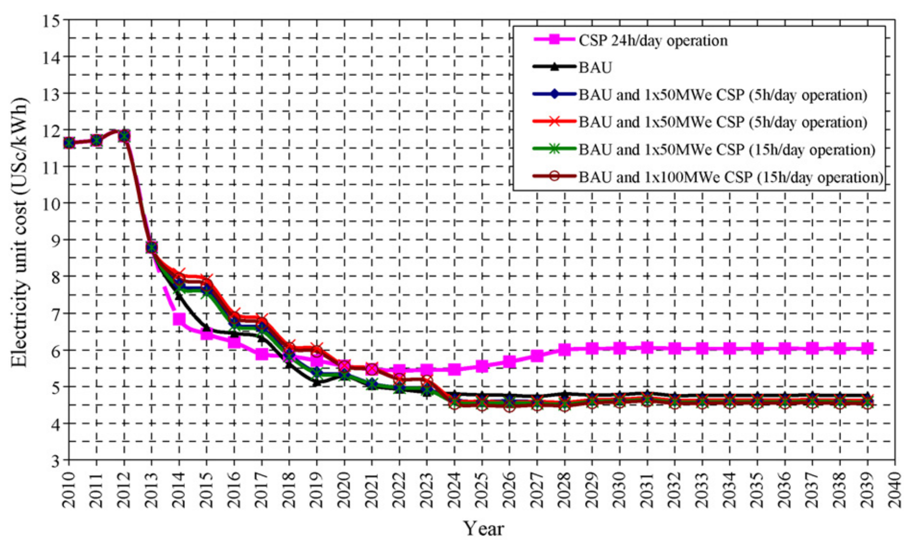

Fig. 7. Generation system annual electricity unit cost in real prices (sensitivity analysis for LNG price 4.9US$/GJ).

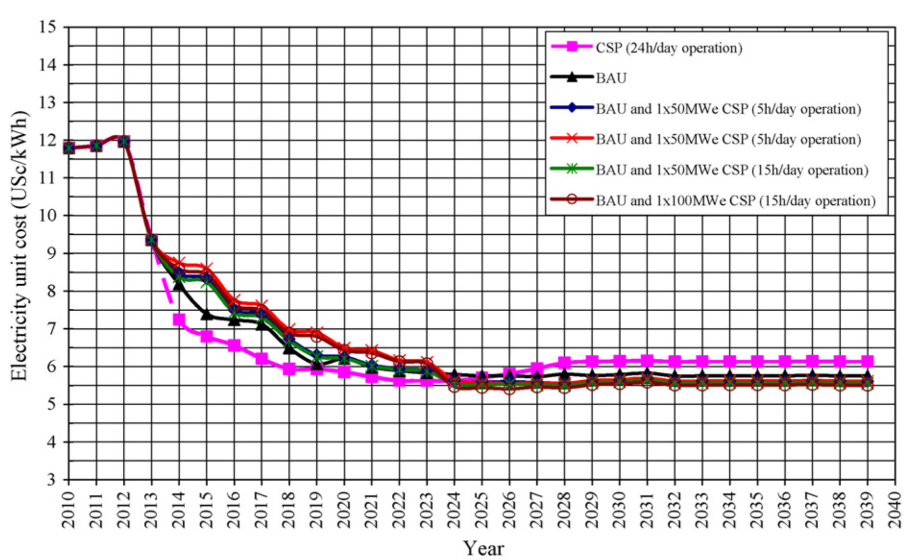

Fig. 8. Generation system annual electricity unit cost in real prices (sensitivity analysis for LNG price 6.4US$/GJ).

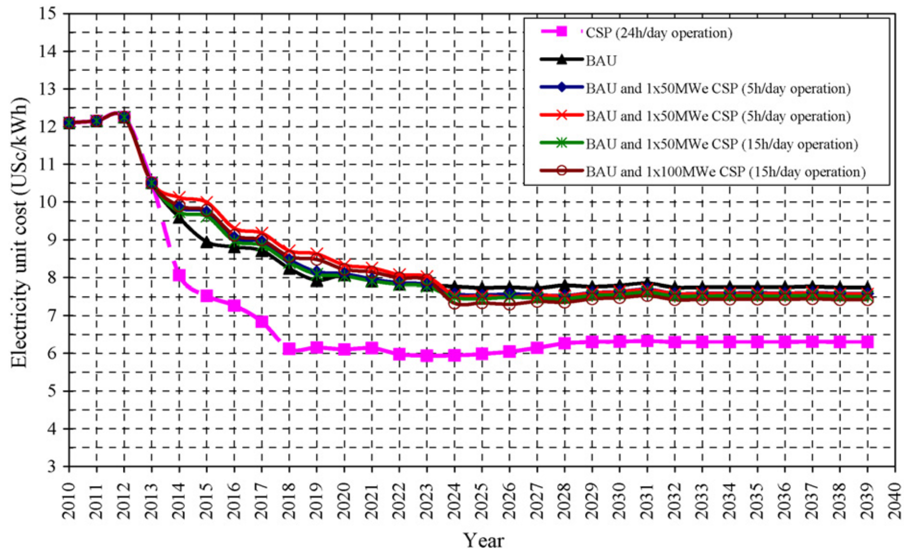

Fig. 9. Generation system annual electricity unit cost in real prices (sensitivity analysis for LNG price 9.4US$/GJ).

5. Conclusions

In this work, a technical and economic analysis was carried out using the WASP IV software package for the investigation of the effect of the expected penetration of parabolic CSP plants (with or without thermal storage capability) on the electricity unit cost of the future Cyprus generation system. A range of candidate scenarios were investigated regarding the optimum planning option (least cost option) in terms of lower electricity unit cost for the future expansion of the Cyprus generation system. The BAU expansion scenario was used as the base case scenario, with alternative scenarios including the commissioning of 50 MWe or 100 MWe parabolic trough CSP plants in year 2014 with or without thermal storage capability.

Based on the input data and assumptions made, the WASP IV simulation analysis shows that the scenario of the Cyprus generation system expansion with a single parabolic trough CSP plant (either 50 or 100 MWe and with or without thermal storage capability, to be commissioned in 2014) in combination with BAU will effect an insignificant change in the electricity unit cost of the system compared to the BAU scenario. This is the case even without including the effect of future feed-in tariff schemes to support 50 or 100 MWe CSP technology plants and future technology improvements in the parabolic trough CSP technology that will serve to bring down the capital cost of CSP plants. Also, increasing LNG prices (e.g. 9.4US$/GJ) make this scenario marginally more economically attractive compared to the BAU scenario.

In addition, the integration of parabolic trough CSP plants with thermal storage capability and of 50 MWe capacity is shown to provide lower system electricity unit costs for the generation system compared to parabolic trough CSP plants of larger capacity (e.g. 100 MWe) or without any thermal storage capability. The option of utilizing only the parabolic trough CSP technologies of 50 MWe capacity with operating hours of 24 h/day (19 h thermal storage) for the future expansion of the generation system is shown to be the most economical option for the future system expansion, however, technological developments and more research are still required before this technology can become commercialized and be properly compared to the technologies investigated in this study.

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